

In particular, it will be important to strike an appropriate balance between the basic research needed to progress these ideas and the required industrialization of the techniques. As an example of this balance, European researchers have just been granted funds from the European Union to pursue the development of laser-driven electron accelerators into the GeV energy regime, with a view to creating reproducible monochromatic beams. Alongside this, a demonstration proton oncology laser system known as “Pro-Pulse” is being pursued by a team led by the Laboratoire d’Optique Appliquée (LOA) in France, with the goal of raising the energy of the proton beam to the required 70- to 250-MeV level. These two ambitious projects will help demonstrate whether laser acceleration of particles is a viable route for fundamental physics

studies and clinical applications.

Looking further into the future, an exciting new proposal is being developed by a consortium of researchers led by Mourou (at the LOA) for ultrarelativistic particle beam lines based on exawatt-class laser technology. This project, known as Extreme Light Infrastructure, is currently under consideration as part of the European Research Infrastructure roadmap process (10). Its goal is to provide multiple accelerator beam lines delivering high-brightness electron, gamma, and proton sources for a wide range of user applications.

It is clear that we are still a number of years away from exploitation of these laser-driven accelerators, but this should not detract from the major advances demonstrated over the past few months. Unprecedented research attention

is being paid to this area, which is already paying dividends as demonstrated by the innovative techniques reported here. This is definitely a field to watch.

References and Notes

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MATERIALS SCIENCE

Self-Assembly of Unusual Nanoparticle Crystals

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The crystallization of matter on any length scale, from atoms and ions to biomolecules to nano- and microparticles, has long been a major thrust in science and technology. On page 420 of this issue, Kalsin *et al.* (1) report the cocrystallization of equally sized metallic nanoparticles into large crystals with diamond-like symmetry. The oppositely charged gold and silver nanoparticles attract each other at very short distances and assemble into unusual lattices. This work provides new insights into crystallization on the nanoscale, and fills in a gap in the overall picture of particle and biomolecule crystallization.

It has been known for decades that micrometer- and submicrometer-sized spheres suspended in liquids readily form “colloidal crystals” during sedimentation or drying. The spheres crystallize when their free volume is restricted below a certain threshold, but this occurs only when the interactions between the spheres are repulsive, which allows their rearrangement. Such closely packed crystals allow facile fabrication of materials with controlled porosity and long-range organization (2). Volume-restricted repulsive spheres, however, always crystallize in a trivial lattice of hexagonally close-packed layers. This limits the range of their application as other types of crystal symmetries are required for photonic, optoelectronic, and memory storage applications.

The formation of colloid crystals with other symmetries can, in principle, be achieved if the particles are assembled by attractive interactions. Two seemingly simple ideas for crystallization by particle attraction have been considered, yet they have proven notoriously difficult to realize experimentally. The first idea is to use binary mixtures of oppositely charged particles that could cocrystallize in a manner broadly similar to crystallization of ionic salts from liquid solutions. The problem with this system is that strongly attractive particles rapidly and irreversibly stick to each other, forming gel-like aggregates. Only recently have Leunissen *et al.* designed a procedure whereby micrometer-sized colloidal spheres having small positive or negative charges are synthesized and cocrystallized in density-matched organic liquids (3). The particles, whose attractive interaction energies are estimated to be on the order of a few $k_B T$ units (where k_B is Boltzmann’s constant and T is temperature), come together in mixed CsCl-type lattices of alternating positive and negative charges. A variety of crystals of other symmetries and particle compositions have been assembled, and the method could be versatile enough to be used in the routine synthesis of ionic colloidal crystals.

A second idea for particle crystallization by attractive interactions that has also proven difficult to realize is the crystallization of particles by functionalizing them with complementary DNA strands. DNA hybridization locks the particles together when they come into contact;

Regular particles of any size, from atoms to colloids, can form crystals. Manipulation of their charges allows control of crystal structure and can be extended to nanoparticle self assembly.

however, the strong irreversible “snapping” into place does not allow crystallization. The key to making this idea work has been to reduce the strength of the interactions by adjusting the temperature of the suspension very near the melting point of DNA, where hybridization is weak and reversible (4). Thus, colloidal crystallization may be achieved by various attractive forces, but only when the interaction energy is precisely adjusted within a certain small range (see the figure).

Systems of nanoparticles 1 to 10 nm in size provide a natural link between the areas of molecular and colloidal crystallization. Crystals from such particles can find applications in nanoelectronics, plasmonics, high-density data storage, catalysis, and biomedical materials. The formation of binary crystals from nanoparticle mixtures as a likely result of cocrystallization under restricted volume conditions was reported some time ago (5). Only recently has the role of electrostatics in the formation of nanoparticle crystals emerged as a parameter that can be controlled in order to assemble various crystals of new symmetry and composition (6). The report by Kalsin *et al.* conclusively proves that large crystals can be produced by controlled electrostatic self-assembly. The crystallization has been achieved by precise adjustment of the attraction between the oppositely charged nanoparticles, but the data also point to the existence of unusual effects of electrostatic screening of the larger particles by the smaller ones that do not scale up to interactions between microspheres.

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